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Goal-directed grasping: The dimensional properties of an object influence the nature of the visual information mediating aperture shaping

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ABSTRACT

An issue of continued debate in the visuomotor control literature surrounds whether a 2D object serves as a representative proxy for a 3D object in understanding the nature of the visual information supporting grasping control. In an effort to reconcile this issue, we examined the extent to which aperture profiles for grasping 2D and 3D objects adheres to, or violates, the psychophysical properties of Weber's law. Specifically, participants grasped differently sized 2D and 3D objects (20, 30, 40, and 50 mm of width) and we computed the just-noticeable-difference scores associated with aperture profiles at decile increments of normalized grasping time. The aperture profiles for 2D objects showed an early through late (i.e., 10% through 90%) adherence to Weber's law, whereas the late stages of grasping 3D objects (i.e., >50% of grasping time) produced a fundamental violation of the law's principles. As such, results suggest that grasping a 2D object is a top-down and cognitive task mediated via relative visual information. In contrast, the enriched shape information provided by a 3D object (i.e., stereoscopic vergence and disparity cues) allows for later aperture specification via absolute (Euclidean) visual information. Most notably, our results establish that the dimensional properties of an object influence the visual information mediating motor output, and further indicate that 2D and 3D objects are not representative proxies for one another in understanding the visual control of grasping.

1. Introduction

The ability to generate a successful grasping movement is dependent on extracting task-relevant properties from an intended target object. For example, it is paramount to know that a cup of coffee offers the possibility for holding and drinking whereas a picture of the same cup offers neither of these. Gibson (1986) recognized how the intrinsic (e.g., weight, height) and extrinsic (e.g., size, location) properties of an object influence behavioral affordances and how the object's 'act on-able' qualities are a product of what action, or actions, it offers the observer. In particular, Gibson stated: "To be graspable, an object must have opposite surfaces separated by a distance less than the span of the hand" (p. 133). It is, however, interesting to note that Gibson's seminal work does not address whether the dimensional properties of an object (i.e., 2D vs. 3D) influence action affordances. Indeed, this is a salient issue because several studies have employed 2D objects as representative proxies for 3D objects in understanding the nature of the visual information mediating goal-directed grasping (e.g., Brown, Halpert, & Goodale, 2005; Hu & Goodale, 2000; Vishton, Rea, Cutting, & Nuñez, 1999).

On the one hand, some work has reported equivalent visual processes for grasping 2D and 3D objects. For example, Westwood, Danckert, Servos, and Goodale (2002) had control participants and a visual agnosic patient (DF)[1] perform a manual estimation (i.e., a perceptual task) and a grasping task in response to the presentation of differently sized 2D and 3D objects. In terms of control participants, manual estimations and grasping responses (as indexed by peak grip aperture: PGA) to both 2D and 3D objects increased with increasing object size and produced comparable linear relations. In terms of DF, her performance on the grasping task, but not the manual estimation task, showed a reliable scaling to object size: a finding that was independent of object dimension. Westwood et al. interpreted their results within the theoretical framework of the perception/action model (Goodale & Milner, 1992). In particular, DF's impaired performance on the manual estimation task was taken as evidence that relative (i.e., scene-based) visual information mediated

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[1] DF has been frequently described in the neuropsychology literature (for review see Goodale, 2011). Briefly, DF has an acquired visual form agnosia arising from bilateral lesions to the lateral occipital cortex of her ventral visual pathway (James, Culham, Humphrey, Milner, & Goodale, 2003). As a result, DF is unable to perceptually identify objects (in particular 2D forms) but demonstrates the preserved ability to use vision for action.

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via the ventral visual pathway is necessary to support top-down and cognitive judgments of object size. In turn, the scaling of PGA to object size observed in both controls and DF was interpreted to reflect that absolute (i.e., Euclidean) visual information mediated via the dorsal visual pathway subserves goal-directed grasping. What is more, Westwood et al.'s observation that 2D and 3D objects produced comparable linear relations between PGA and object size lead them to conclude that "[T]he dorsal stream grasping system does not discriminate in a fundamental way between 2D and 3D objects" (p. 262). In a similar vein, Kwok and Braddick (2003) showed that PGAs for grasping 2D and 3D objects embedded within a pictorial illusion (i.e., Titchener circles) were refractory to the context-dependent properties of the illusion (i.e., relative visual information), whereas manual estimations of the same objects were reliably 'tricked'. As such, the authors concluded that grasping 2D and 3D objects operates independent of relative visual information and that the motor system is restrictively mediated via absolute visual information (but see Coello & Grealy, 1997; Conti & Beaubaton, 1980; Krigolson & Heath, 2004; Krigolson, Clark, Heath, & Binsted, 2007).

On the other hand, some evidence suggests that dissociable visual information subserves the grasping of 2D and 3D objects because the former lack fundamental grasping attributes and the latter provide enriched shape information such as stereoscopic vergence and disparity cues. Indeed, 3D objects permit the computation of grasp points (i.e., position of the thumb and fingers at object contact) based on the absolute and 'act on-able' visual properties of the object as well as the intended goal of the response (e.g., grasp to hold vs. grasp to lift and place) (Smeets & Brenner, 1999; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987; MacKenzie & Iberall, 1994). In contrast, a 2D object requires that participants adopt a cognitive representation for determining appropriate grasp points. In other words, the participant, and not the physical properties of the object, determines an appropriate tolerance for successful grasping. Moreover, electrophysiological studies of non-human primates have shown that neurons within dorsal and ventral visual processing areas demonstrate selective activation in response to object identification via binocular disparity cues (i.e., 3D objects) (Maunsell & Van Essen, 1983; Roy, Komatsu, & Wurtz, 1992; Taira, Tsutsui, Jiang, Yara, & Sakata, 2000; Janssen, Vogels, & Orban, 2000). As well, recent human *f*MRI work by Snow et al. (2011) demonstrates that the presentation of 2D and 3D objects engenders dissociable activation within dorsal and ventral visual processing regions. Thus, a corollary drawn from convergent neurophysiological evidence is that distinct neural processes support the *grasping* of 2D and 3D objects.

The goal of the present investigation was to determine the extent to which aperture shaping for 2D and 3D objects adheres to, or violates, the psychophysical principles of Weber's law. In particular, Weber's law states that changes in a stimulus that will be 'just noticeable' is a constant ratio of the original stimulus magnitude and that the sensitivity of detecting a change in any physical continuum is *relative* as opposed to *absolute*. Thus, the just noticeable difference (JND) for weaker stimuli is smaller and the resolution is greater than more robust stimuli in the same sensory continuum. As such, a comparison of the JNDs for grasping 2D and 3D objects provides a direct basis for determining whether the dimensional properties of an object influence the visual information supporting aperture shaping. In previous work by our group, participants manually estimated and performed visually (Heath, Mulla, Holmes, & Smuskowitz, 2011) and memory-guided (Holmes, Mulla, Binsted, & Heath, 2011) grasping responses to differently sized (20, 30, 40, 50 and 60 mm) 3D objects. Notably, within-participants standard deviations of grip aperture size were used to determine participant's sensitivity to detecting changes in object size (i.e., the JNDs) (see also Ganel, Chajut, & Algom, 2008). As well, JNDs in the grasping task were measured at decile increments of normalized grasping time to determine whether aperture shaping is mediated via unitary or dissociable visual information. Results for the manual estimation task showed that JNDs increased linearly as a function of increasing object size; that is, the trial-to-trial stability of participants estimation of the size difference between their grip aperture (i.e., the comparator stimulus) and the target object decreased as a function of increasing stimulus intensity (i.e., the object size). Thus, manual estimations adhered to Weber's law and demonstrate that relative visual information supports perceptual judgments of object size. In terms of grasping responses, visually and memory-guided grasping showed a linear scaling of JNDs to object size during the early (i.e., 10% through 50% of grasping time) but not late (i.e., 60% through 90% of grasping time) stages of aperture shaping. These findings demonstrate an early adherence and late violation to Weber's law. In line with Glover's (2004) planning/control model, our group attributed the time-dependent adherence to Weber's law as evidence that relative and absolute visual information contribute to the early and late specification of grip aperture, respectively.

In the present study, participants manually estimated and grasped differently sized (20, 30, 40 and 50 mm) 2D and 3D objects. As in previous work (Heath et al., 2011; Heath, Holmes, Mulla, & Binsted, 2012; Holmes et al., 2011), JNDs for the grasping task were computed at decile increments of normalized grasping time. In terms of research predictions, if the motor system does not discriminate between the dimensional properties of an object (e.g., Westwood et al., 2002) then aperture trajectories for 2D and 3D objects should exhibit a time-dependent early adherence and late violation of Weber's law. In turn, if grasping a 2D object requires the top-down and cognitive mediation of appropriate grasp points then such actions should demonstrate a time-independent adherence to Weber's law. In other words, results would suggest that unitary and relative information mediates the grasping of a 2D object. Of course, support for the latter prediction would indicate that 2D and 3D objects are not representative proxies for one another in understanding the visual control of action.

2. Methods

2.1. Participants

Twelve (three males, nine females: age range 18–24) self-declared right hand dominant participants with normal or corrected-to-normal vision were recruited from the University of Western Ontario community. Participants provided written informed consent prior to their participation and this project was approved by the Office of Research Ethics, the University of Western Ontario, and was carried out according to the Declaration of Helsinki.

2.2. Apparatus and procedures

Participants stood in front of a table-top (880 mm high: depth and width of 740 and 1040 mm, respectively) and manually estimated the size (i.e., the perceptual task) or grasped (i.e., the grasping task) 2D and 3D targets (see details below) using the thumb and forefinger of their right hand (so-called precision grasp). 2D targets consisted of printed stimuli presented against a neutral white background and were 10 mm in depth and 20, 30, 40, and 50 mm in width. 3D targets were acrylic blocks presented against the same background as the 2D objects and were the same depth (i.e., 10 mm) and width (i.e., 20, 30, 40 and 50 mm) as the 2D objects but involved a height of 10 mm. All targets were printed/colored as a matching flat black. Targets were presented at a common midline location 450 mm from the front edge of the table-top (i.e., in the depth plane) and were oriented with their long-axis perpen-